Radiometric Compensation and Calibration for Radarsat ScanSAR

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Abstract

Due to lack of a standard for modeling the radar echo signal in terms of signal unit and coordinates as well as lack of a standard in designing the gain factors in each stage of a processor, absolute radiometric calibration of a SAR system is usually performed by treating the sensor and processor as one inseparable unit. This often makes the calibration procedure complicated and requiring the involvement of both radar system engineers and processor engineers in the whole proms. This paper introduces a standard for modeling the radar echo signal and a standard in designing the gain factor of a ScanSAR processor. In this paper, the radar equation is derived based on the amount of energy instead of the power received from a backscatterer. These efforts lead to simple and easy-to-understand equations for radiometric compensation and calibration.

1. INTRODUCTION

This paper describes the radiometric compensation algorithm proposed for the Radarsat ScanSAR processor. A detailed analysis for the radar signal and noise energy distribution is also given to facilitate the understanding of the compensation equation. A radiometric calibration procedure similar to that applied to the Magellan SAR data is then described.

It starts with the discussion of proper scaling for the SAR raw data. It then shows the scale factors that must be incorporated in each stage of the processing module for designing a unit gain processor. Signal and noise analysis in terms of energy arc introduced then. It follows by the description of the radiometric compensation process and calibration steps.

2. UNITS OF SAR SIGNAL, AND COORDINATES

The original radar signal is one dimensional with its unit given by voltage. Its instantaneous power can be formulated by the square of the signal times the reciprocal of the output impedance of the receiver. The energy over a time period is given by the integration of the instantaneous power over that period. This can be expressed by

$$E_t = \int Z^{-1} \cdot S^2(\tau)\, d\tau \qquad (1)$$

For a SAR system, a SAR processor engineer usually treats its signal as a two dimensional one with one coordinate named the fast time τ and another coordinate named the slow time t. In this case, the interpretation of the unit of the SAR signal may require some consideration. A simple approach is to make a reasonable assumption that the two-dimensional integration of the square of the signal is equal to the total signal energy. This can be expressed by

$$E_t = \iint S^2(t, \tau)\, dt\, d\tau \qquad (2)$$

In order for (2) to be consistent with (1), S' (t, τ) must equal to the product of $S(7)$ and $\sqrt{PRF / Z}$ where PRF is the pulse repet i tion frequency. Thus, the' unit of the SAR input signal becomes (joule·Hz)$^{1/2}$. Since digital SAR data is quantized by the quantization level of the ADC, dV, the scale factor for the SAR raw data must also include dV. Therefore, one must convert a SAR input signal by a scale factor of $\sqrt{PRF / "Z} \cdot dV$ before input to the SAR processor.

3. SAR CORRELATION WITH UNITY GAIN

For a burst mode SAR like the Radarsat ScanSAR, the correlation process involves fast Fourier correlat ion in range and azimuth deramp-FFT process. Both processes may int roduce additional gain if they arc not properly scaled. To ensure unity gain from SAR correlat ion process, the standard process described below should be followed.

A fast Fourier correlation is an implementation approach for a correlation or convolution process through the usc of FFT algorithm. In a range compression process, the convolution can be expressed by

$$R(t) = \int C(\tau)\ g_r(t - \tau)\ d\tau$$

where $C(t)$ is the range echo data and $g_r(.)$ is the range reference function designed for both resolution compressing and impulse response shaping. Since $C(t)$ is a random process, in order to maintain $\int R^2(t)\,dt = \int C^2(t)\,dt$, the following condition must be satisfied

$$\int g_r^{\,2}(t)\ dt = 1$$

Also to be noticed is that the gain of the standard FFT is not the same as that of a Fourier transform. A Fourier transform is given by

$$\hat{S}(f) = \int S(t)\ e^{-j\ \omega\ t} dt$$

In discrete form, it is given by

$$\hat{S}(k\ \Delta f) = \sum_{1}^{N} S(i\ \Delta t)\ e^{-j\ 2\pi\ i\ k\ \Delta f\ \Delta t}\ \Delta t$$

A conventional FFT routine gives a normalized result such that a factor of Δt is ignored, i.e.,

$$\hat{S}(k\ \Delta f) = \sum_{1}^{N} S(i\ \Delta t)\ e^{-j\ 2\pi\ i\ k\ \Delta f\ \Delta t}$$

Therefore, in evaluating the signal power in spect ral domain, the gain of the power differs *by* a factor of Δt^2. Based on this, the following steps must be implemented in the Radarsat ScanSAR process:

[1] in range compression, after the forward FFT, a factor of Δt must be mult i plied to the spectrum, where Δt *is* the range sampling interval.

[2] In range compression, after the inverse FFT, a factor of $\Delta f = f_s/N_{fft}$ must be multiplied to the spectrum, where f_s is the range sampling frequency and N_{fft} is the range FFT length. However, standard inverse FFT does have a scale factor of $1/N_{fft}$, therefore, the factor to be multiplied is f_s. It should be noted that the scale factor introduced in step [2] is the reciprocal of the scale factor int roduced in step [1].

[3] In azimuth compression, after FFT, a factor of $\Delta t = 1/PRF$' *must* be multiplied to the spectrum.

in azimuth processing for the ScanSAR data, the deramp reference function is the composite function of the deramp phase function and a weighting function. The deramp phase function does not affect the radiomet ric gain, but the weighting function could int reduce a gain factor. To ensure unity gain in azimuth processing, the weighting function must be normal ized, i .e.

$$\sum_{1}^{N_p} w^2(k\ \Delta f)\cdot \Delta f = PRF \quad \text{or} \quad \sum_{1}^{N_p} w^2(k\ \Delta f) = N_p$$

4. SIGNAL ENERGY FROM TARGET

Let the power and duration of a radar pulse given by P_t and τ_p respectively, the energy contained in a burst of radar pulses is then given by

$$E_t = N_p \int_0^{\tau_p} P_t\, dt = N_p\ P_t\ \tau_p$$

where Np is the number of pulses in the radar burst. The energy of each radar pulse is distributed to all directions in the space with a percentage proportional to the gain of the antenna pattern. In a SAR system, the radar beam is pointed to the ground, therefore, this energy is finally distributed to areas within the antenna footprint. If the burst interval is relatively short, the amount of along-track migration of the antenna footprint during the burst interval will be small as compared to the dimension of the footprint. Under this assumption, wc may consider that the energy of all Np pulses is distributed to the footprint with the same distribution function as that of a single pulse. For a small area dA within the footprint, the amount of energy reflected in a burst of radar pulses is given by

$$E_r = N_p\ P_t\ \tau_p \frac{G(\theta,\phi)}{4\ \pi\ R^2} \cos\theta_L\, dA$$

where R is the distance between the radar and the target, $G(\theta,\phi)$ is the antenna gain, and Of, is the radar look angle. Let σ be the cross section of a point-like target, the energy reflected from this target is then given by

$$E_1 = N_p\ P_t\ \tau_p\ \frac{G(\theta,\phi)}{4\ \pi\ R^2}\ \sigma$$

If the scatterer is iso-tropic, the energy received by the radar antenna from the signal reflected from dA is given by

$$E_2 = N_p\ P_t\ \tau_p \frac{G(\theta,\phi)\, A_e}{(4\ \pi\ R^2)^2}\ \sigma \tag{3}$$

where Ae is the effective antenna area. Since Ae is given by $(\lambda^2/4\pi)G(\theta,\phi)$ and the receiver gain can be expressed by G_r, the energy received by the receiver can be rewritten as

$$E_2 = N_p\ P_t\ \tau_p\ G_r \frac{G^2(\theta,\phi)\ \lambda^2}{(4\pi)^3\ R^4}\ \sigma$$

For a distributed target, a cross section is substituted by the integral of the product of the backscattering coefficient σ_0 and an infinitesimal area of the target dA, i.e.

$$E_2 = N_p\ P_t\ \tau_p\ G_r \int_A \frac{G^2(\theta,\phi)\lambda^2}{(4\pi)^3 R^4}\sigma_0\ dA \tag{4}$$

5. NOISE ENERGY

The noise power of a radar is usually modeled by

$$P_n = K\ T_e\ B\ G_r$$

where K is Boltzmann's constant, T_e is the equivalent noise temperature, and B is the bandwidth of the radar receiver. Within a collected burst echoes, the total noise energy is given by

$$E_n = K\ T_e\ B\ G_r\ N_p\ \tau_{echo}$$

The amount of noise energy over a fraction of the echo duration $d\tau$ and a fraction of the frequency band width df can be expressed as

$$E_n = K\, T_e\, B\, G_r\, N_p\, d\tau\, \frac{df}{PRF} \tag{5}$$

in ran~e-Doppler image domain, the amount of area covered by the corresponding window of $d\tau\, df$ can be shown to be $dA = dx\ dy$, where $dx = c\ d\tau/(2\sin\theta_i)$ and $dy = \lambda\, R\, df/(2V_s\ \sin\ \theta_{sq})$, R is the distance between the radar and the target, θ_i is the incidence angle, and θ_{sq} is the radar squint angle. Equation (3) can therefore be rewritten as

$$E_n = K\ T_e\, B\, G_r\, N_p\, dx\ dy\, \frac{4V_s \sin\theta_i \sin\theta_{sq}}{c\,\lambda\ R\ PRF} \tag{6}$$

From the signal and noise energy given in *(4)* and (6), the signal-to-noise ratio can be formulated as

$$SNR = \frac{P\ G^2(\theta,\phi)\lambda^3(c\ \tau_p/2)\ \sigma_0\ PRF}{2\,(4\ \pi)^3 V_s\ R^3(K\,T_e B)\ \sin\ \theta_i \sin\ \theta_{sq}}$$

6. GEOMETRIC RECTIFICATION WITH UNITY GAIN

in burst mode SAR processing, a range-Doppler image is formed a fter range and azimuth compression processes. To allow mosaicking for image framelets obtained from SAR bursts, geometric rectificat ion must be made for each range-Doppler image. As shown in section ?, there are conversion factors between the delay time and the cross-track ground distance and between Doppler frequency and along-track ground distance. To preserve energy level, these conversion factors must be properly applied to the recti fied framelets. in equat ion form, it is given by $E_1\, d\tau\, df = E_2\, dx\, dy$. It is obvious that the scale factor S = E_2/E_1 should be equal to

$$S = \frac{d\tau\ df}{dx\quad dy} = \frac{4\ V_s\ \sin\ \theta_i\ \sin\ \theta_{sq}}{c\ \lambda\ R} \tag{7}$$

in Radarsat ScanSAR processing, two elevation maps will be used; a smooth geode model and a fine DEM. When a fine DEM is applied, the above scale factor will vary significantly within the radar footprint such that it must be computed frequently. If a smooth geode is applied, S could be a single constant for the whole framelet.

in implementation, wc may consider to combine this scale factor multiplication with the radiomet ric compensation process to reduce the overall computation load. If it is done in the geomet ric rectification process, $\sqrt{S}$ instead of S should be used since the signal is still in amplitude instead of intensity (amplitude square).

7. RADIOMETRIC COMPENSATION EQUATION

Now wc may formulate the radiomet ric compensation equation under the assumption that (1) the range and azimuth compression processes arc with unity gain, (2) the geomet tic rcct ificat ion is already compensated by the scale factor given in equation (7), and (3) the final image framelet represents the normalized backscattering coefficient. '1'hen, based on equation (4), the radiometric compensation equation is

$$\sigma_0(x, y) = I_n^2\,(x, y) \cdot \frac{4\ \pi^3 R^4}{\tau_p N_p P_t G_r G^2\,(\theta, \phi)\lambda^2} \tag{8}$$

where $I_n^2(x, y)$ is the square of the framelet pixel value in unit of joule/meter ^{2} if the radiometric compensation process not performed, P_t is the transmitted radar pulse power in watt, and G_r is the net receiver gain which includes gain factors from the antenna down to the ADC.

To output pixel with value in term of the backscattering coefficient, the gain factor of $4\pi^3 R^4 (\tau_p N_p P_t G_r G^2(\theta,\phi)\lambda^2)^{-1}$ should be multiplied to the SAR framelet data in the radiometric compensation process which is usually done right before or after the geometric rectification process.

The above equation is useful to come to the understanding of the radiometric compensation, but, it is difficult to realize due to many unknown factors like G_r, Z, and P_t. A practical approach is to model all the unknown factors through the radiometric calibration process. 'l'his calibration process will be described below.

8. RADIOMETRIC CALIBRATION

When the gain of a SAR processor is unity, the radiometric calibration can be broken down as the processes to calibrate the sensor and to verify the processor gain of being unity.

To calibrate the sensor, it may be accomplished by (1) model the gain factor g_1 of the link between the transmitter end and the antenna end which may involve a cable and the antenna itself and (2) to collect a rechirp from an attenuated echo box directly connected to the transmitter end and to compute the sensor gain based on the attenuation factor, the transmitter power, the radar pulse width, and the energy of the collected echo at the end of an ADC. This calibration will give us a constant representing the product of the uncertain factor of the transmitter power and the receiver gain from the transmitter end to the ADC digital output. This calibration constant times the product of the estimated radar power and the gain factor g_1 will be used to replace the product of $1/(P_t G_r)$ in equation (8).

To verify that the gain of the processor is uni ty, wc need (1) simulated raw data of either a point-target response or a Gaussian random process, (2) an assumed set of radar parameters including PRF and range sampling frequency, (3) an assumed set of radar platform parameters including radar position, velocity, terrain elevation, and radar look angle. The SAR raw data will be processed with a set of processing parameters derived from data given in step (2) and (3). 't'his process will, however, exclude the radiometric compensation process. To satisfy the verification of processor, the total energy after this process should be equal to the total energy in the raw data.

9. CONCLUSION

Some scale factors arc ignored in the above analysis for simplification. These may include the scale factors introduced along range as an automatic gain control for the range intensity variation, the transmit ter power variation factor, the receiver gain varia t ion factor, and the at mosphere at tenuat ion factor.

The radiometric compensation process for Radarsat ScanSAR data is given in this paper. 'I'his process requires a unity gain processor which has the advantage that the signals in all modules are calibrated such that they can be used for measuring the amount of energy. The concept of this processor is simple, clear, and easy for implementation. The sensor calibration requires to collect only one radar pulse echo reflected from an echo box. This should not be difficult to obtain.

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